Search for New Physics with the Fermilab Neutrino Beam

Adam Para,
Fermilab, June 19, 2012
2012 Project X Physics Study

Neutrino Physics circa 1995

- Tantalizing suggestions:
  - Neutrinos have mass?
  - Flavor non-conservation?
  - Neutrino oscillations?
- Two prongs:
  - Natural: large mass difference, very small mixing angle ←→ Short baseline oscillation experiments
  - Unnatural: large mixing angle, very small mass difference ←→ Long baseline oscillation experiments

Short baseline experiments, 1995

- CHORUS/NOMAD: nu tau appearance probability < 10^{-4}
- Mixing angles are expected (naturally) to be very small, hence
- Second generation of short baseline oscillation experiments: huge amount of detailed simulations and detector design work:
  - COSMOS
  - TENOR
  - TOSCA
  - NAUSICAA
  - ESTAR

SuperKamiokande bombshell

- Neutrino oscillations
- Very small mass difference
- Neutrino oscillations very strongly suppressed (~absent) at short baseline
- Sudden death of all short baseline oscillation experiments

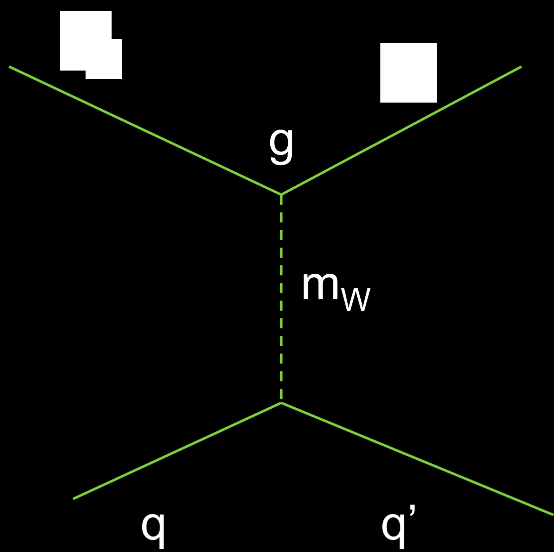
Particle Physics circa 2010

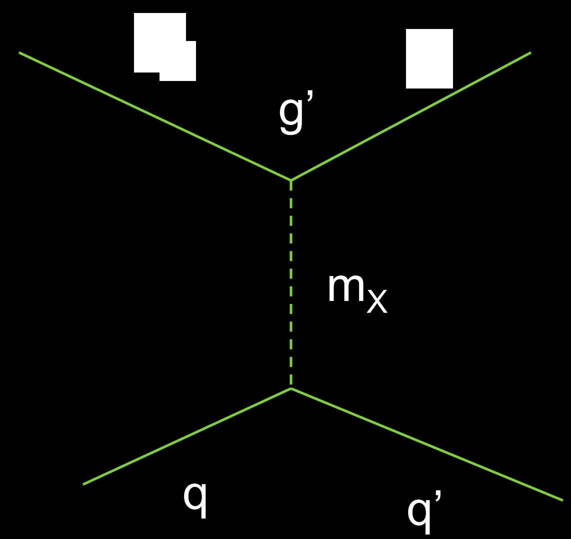
- Neutrino oscillations well established, mass differences and mixing angles pretty well known
- Standard model expected to be incomplete, new physics expected in the range ~ few hundred GeV
- Standard model spectacularly successful: no detectable deviation (other than the neutrino masses). What does it mean?
  - Mass/energy scale of the new physics much larger? Multi TeV or higher?
  - Some symmetries/cancellations reducing the contribution of new physics to the investigated processes?

Broader Search for the New Physics? Neutrinos?

- (Almost?) every extension of the standard model leads to detectable effects in the neutrino sector
- Neutrino processes involving the third generation (taus/tau neutrinos) may be particularly complementary to the other searches for the non-standard interactions
- Neutrino oscillations may hide the effects of the new interactions (Nobel Prize of yesterday a tomorrow's background)
- Remember the fate of the short baseline oscilaltion experiments?? Neutrino oscillations are 'not observable' at the short distance: → short baseline appearance experiments are particularly sensitive probes of new physics

Sensitivity to New Physics





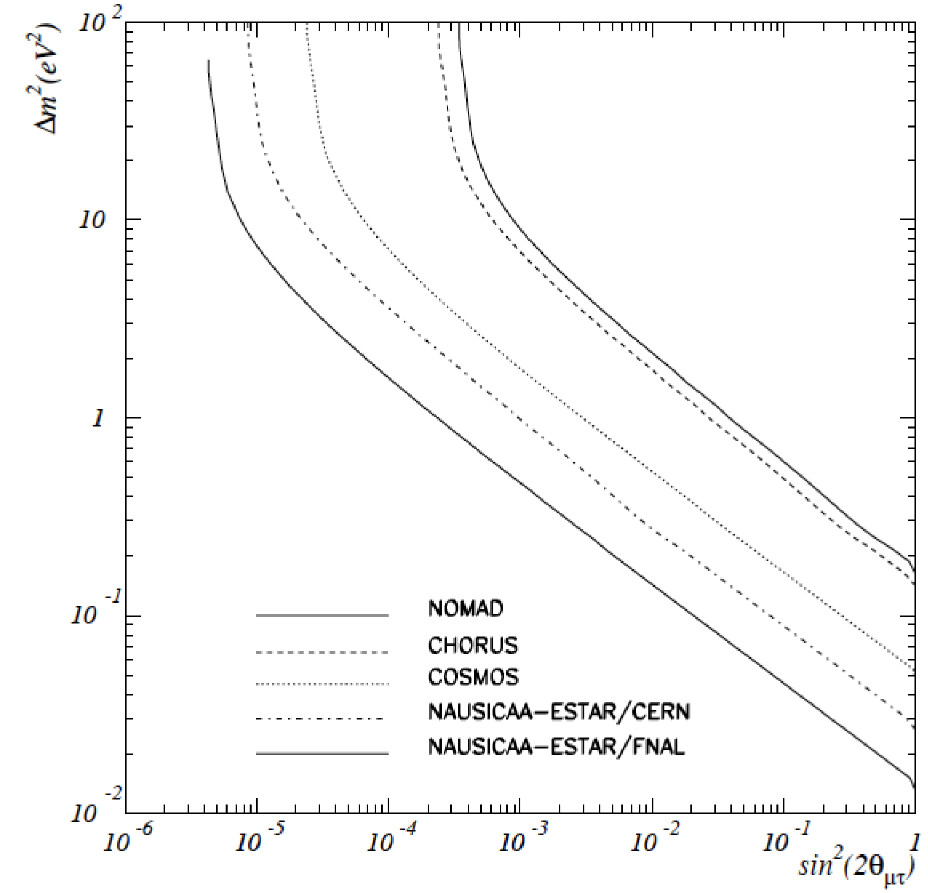
$R =$

If g~g’ and R < 10^{-6} ➔ M_X>2500 GeV

Search for $\nu_\mu(\nu_e) \leftrightarrow \nu_\tau$ Oscillations with a Detector Based on a Emulsion-Silicon Target

J.J. Gomez-Cadenas[1,2] and J.A. Hernando[2,3]

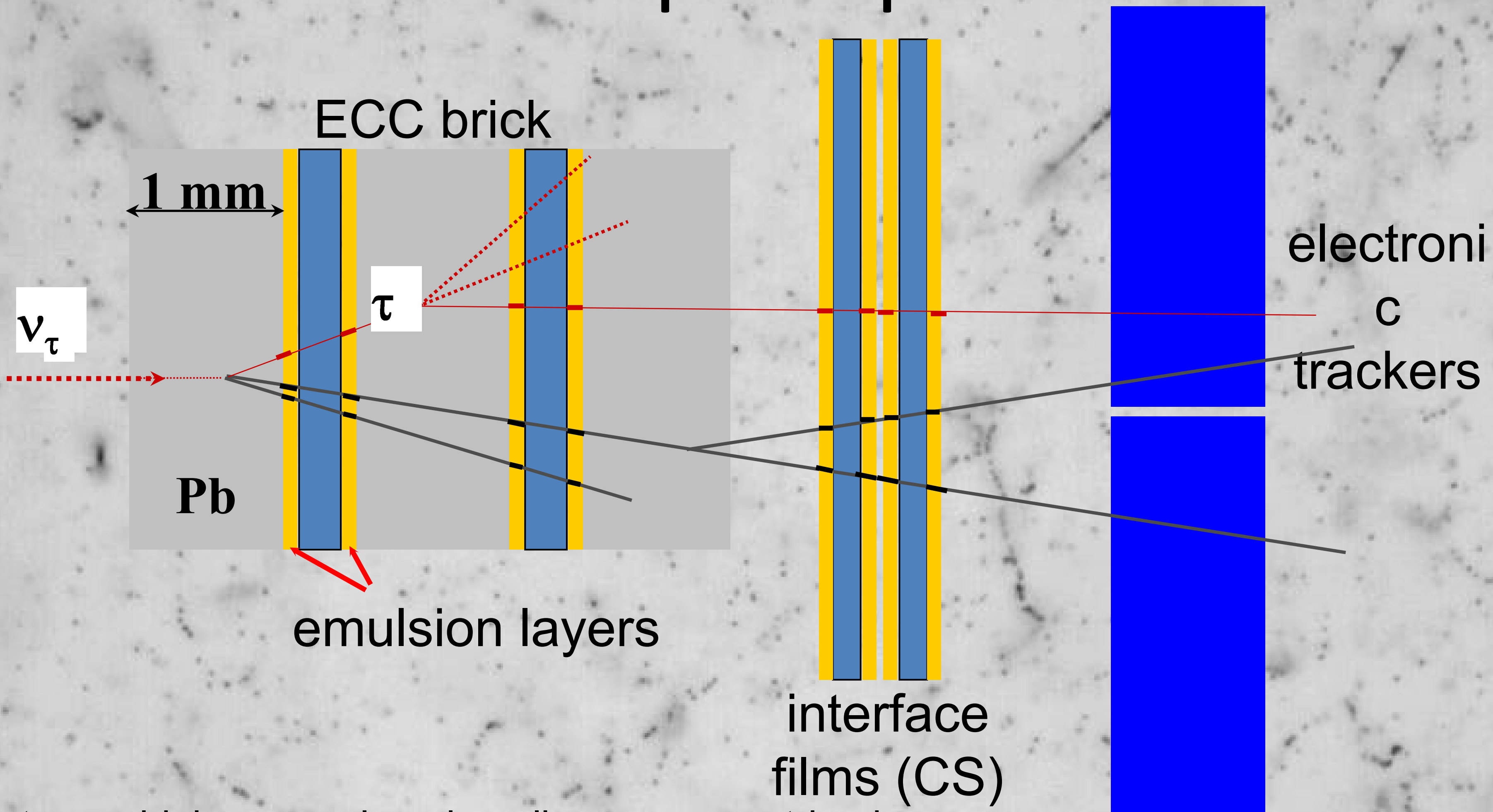
It is possible to improve the limit on the numu to tau conversion by about two orders of magnitude, or discover the new physics using the state of the art experimental techniques and planned NuMI neutrino beam (1995)



From 1995 to 2010

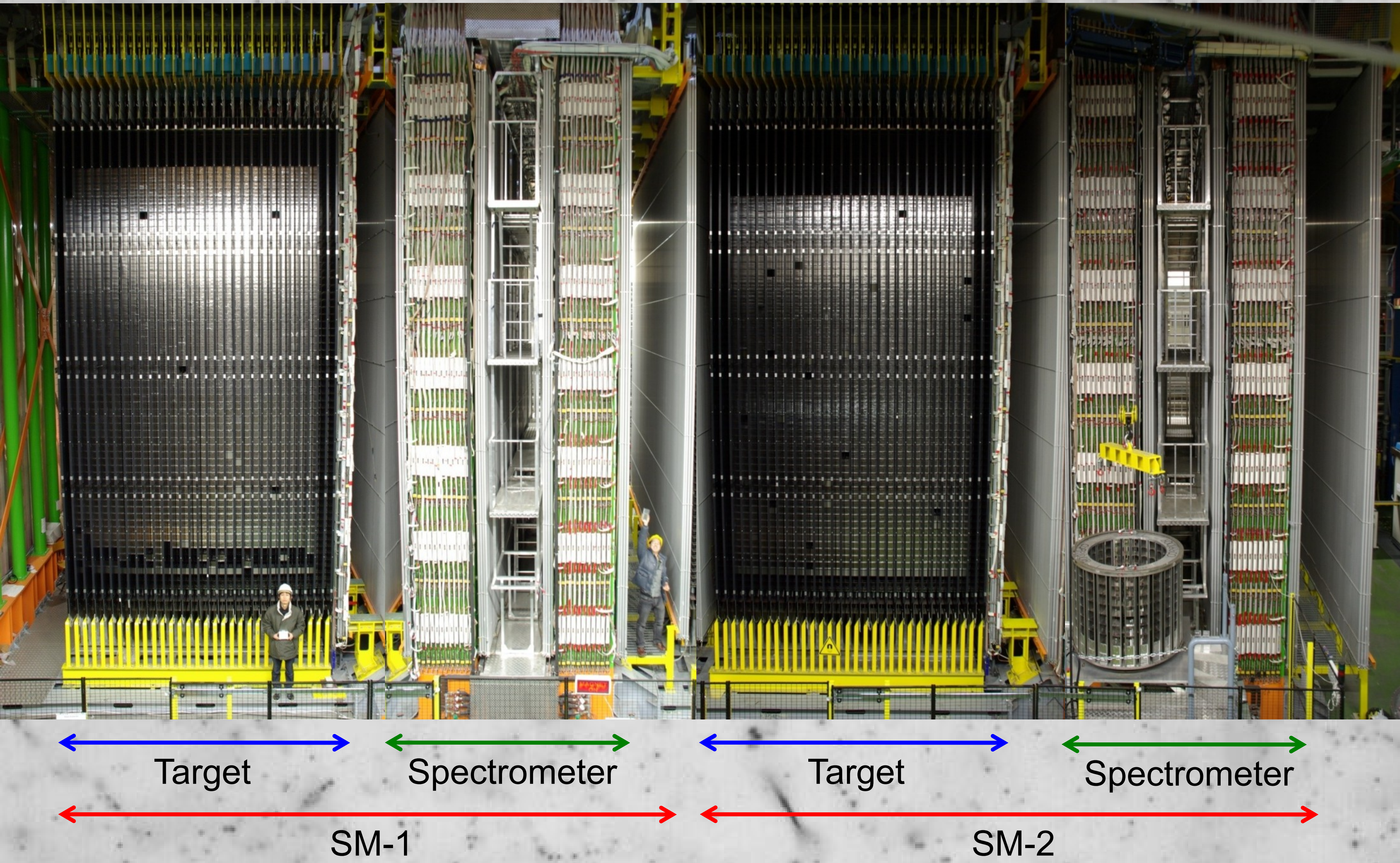
- Tau neutrino interactions observed (DONUT)
- New emulsion techniques proven to be superior, cheaper and easier to the bulk emulsions (DONUT)
- Dramatic increase in the speed and efficiency of the automatic scanning techniques
- Huge, 2 kton, tau appearance experiment constructed and operating (OPERA)
- Silicon tracking (strips and/or pixels) well established technology. Huge area silicon detectors constructed and operating (CDF, D0, CMS, ATLAS)
- High intensity neutrino beam (NuMI) constructed and operating. Major upgrade underway, to be completed in ~ 2 years.

The principle



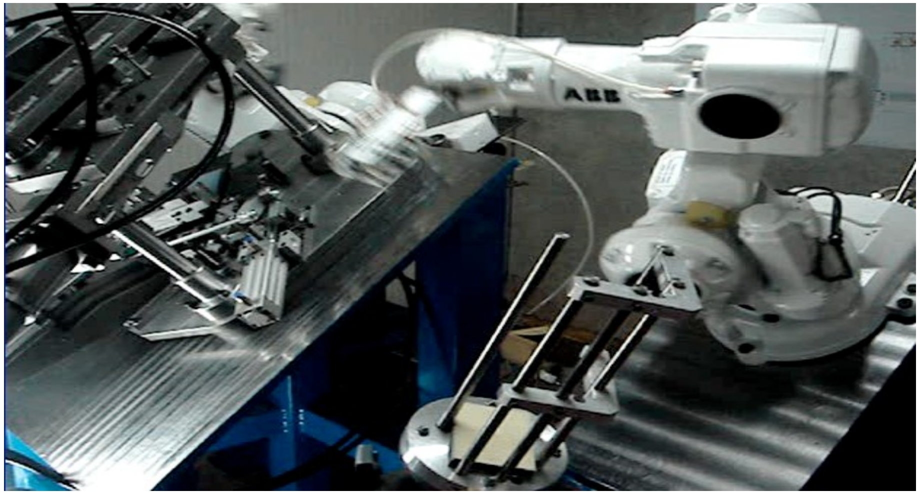
- Intense, high-energy long baseline muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Underground location
- Use electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region

OPERA detector



Ancillary facilities

BAM – Brick Assembly Machine

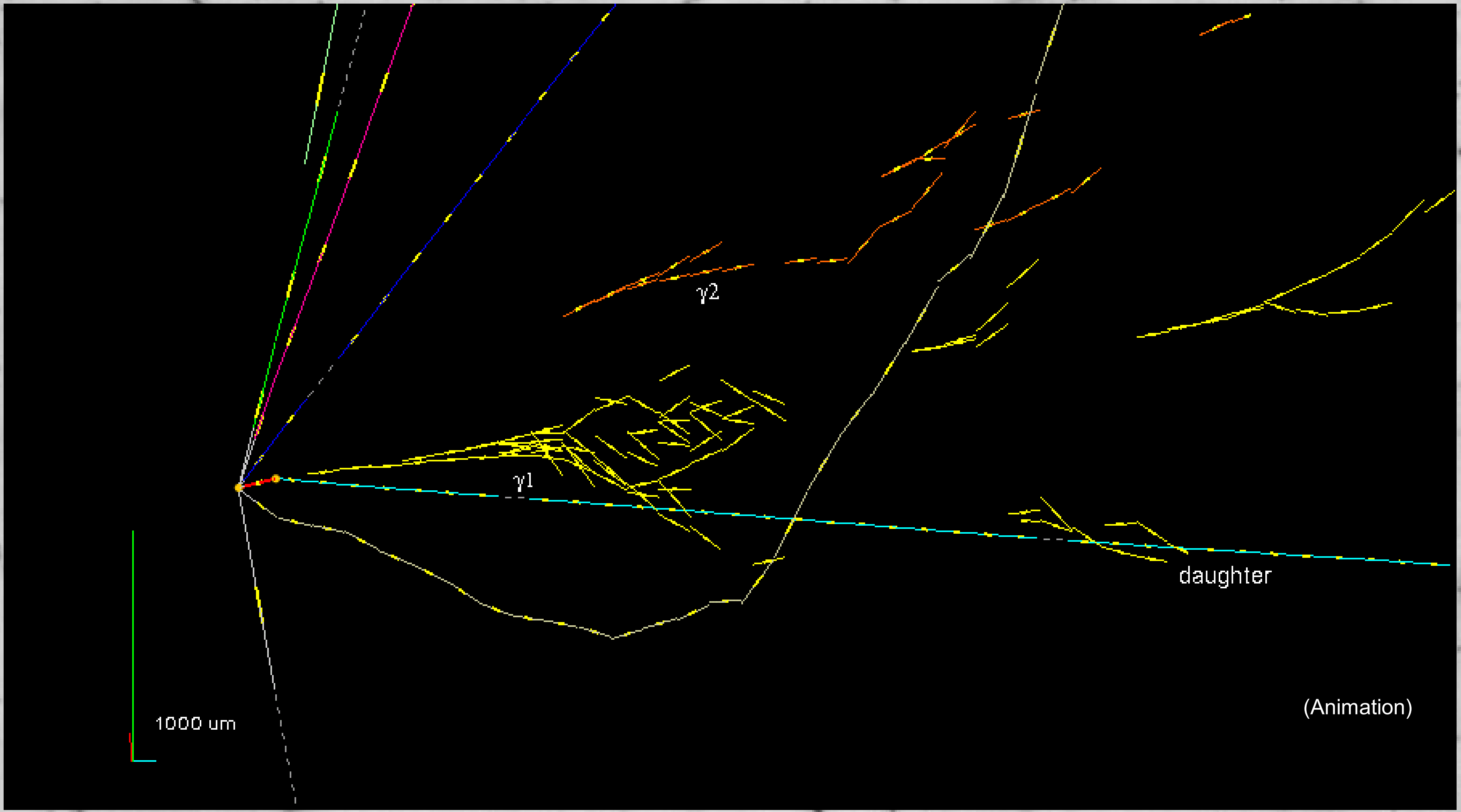


Film development facility

BMS – Brick Manipulator Machi

And, furthermore, CS refreshing, X-rays marking, CS development, cosmic rays exposure, emulsion shipment to labs

...and as seen in emulsion



MINSIS: Main Injector Non Standard Neutrino Interactions Search?

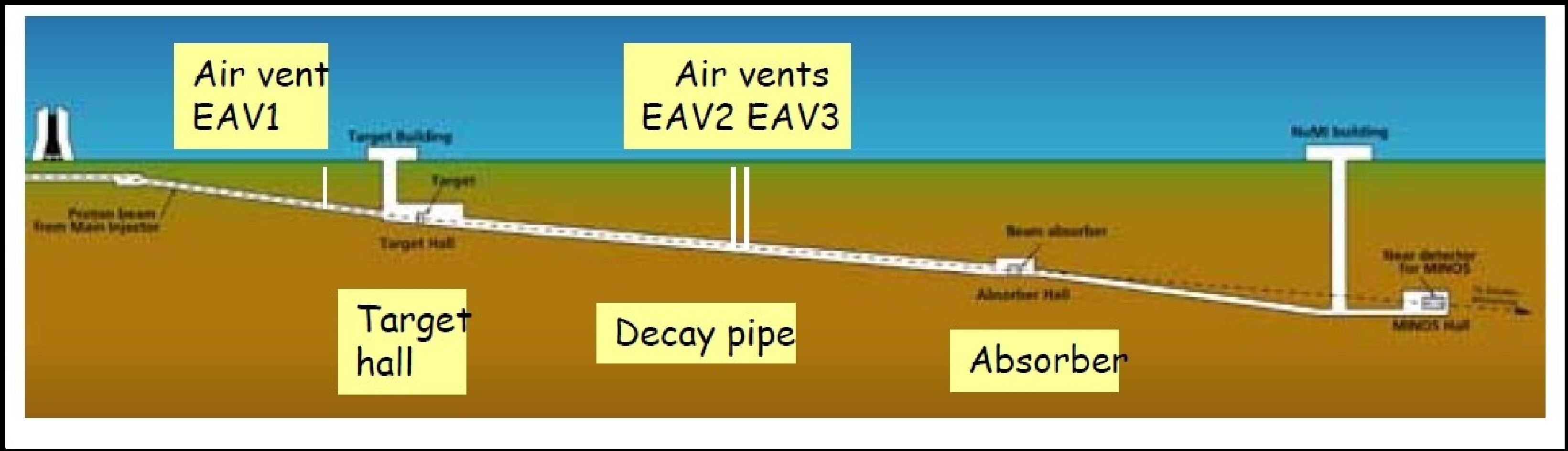
- Proposition:
  - use the upgraded NuMI neutrino beam
  - take advantage of the huge investment in the design of the short baseline neutrino oscillation
  - Take advantage the enormous progress of the experimental techniques (emulsions, scanning, silicon)
  - Take advantage of the suppression of the oscillation background at short distances

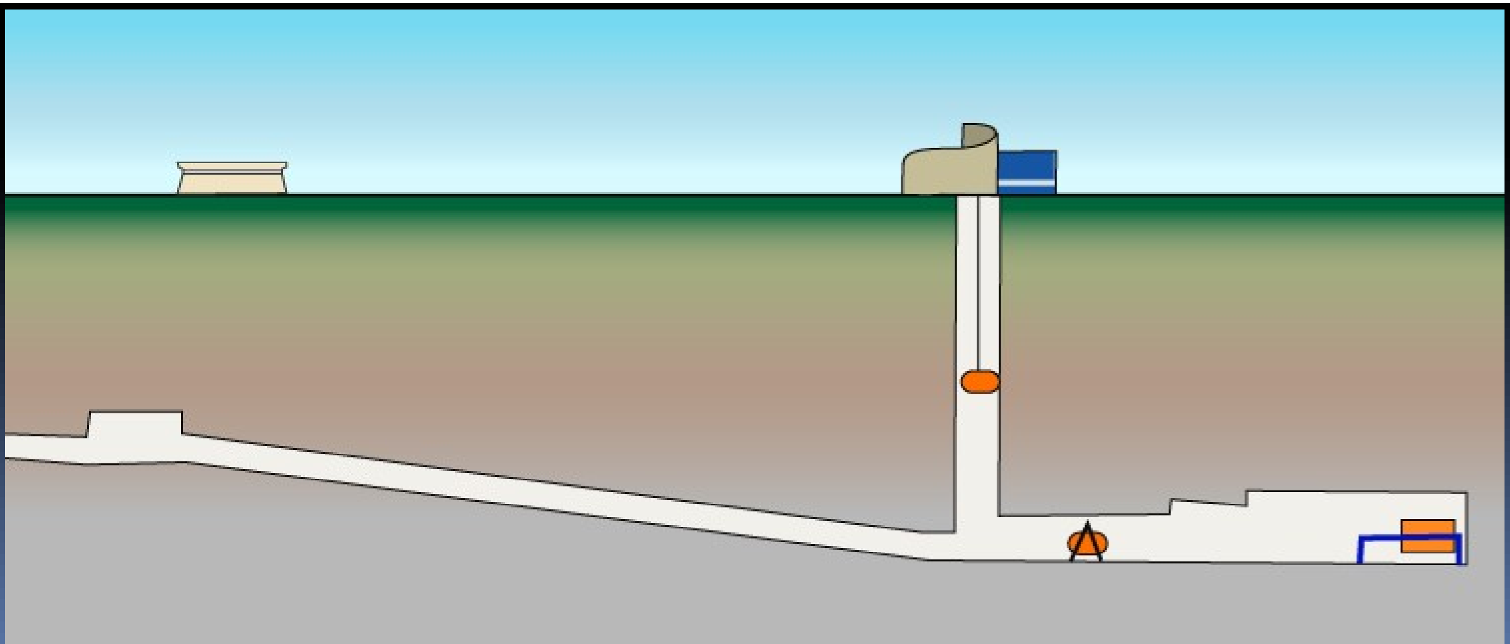
to extend the search for the rare numu-to-tau conversion with the sensitivity up to ~ 10^{-6}

MINSIS: three fundamental (and related) questions:

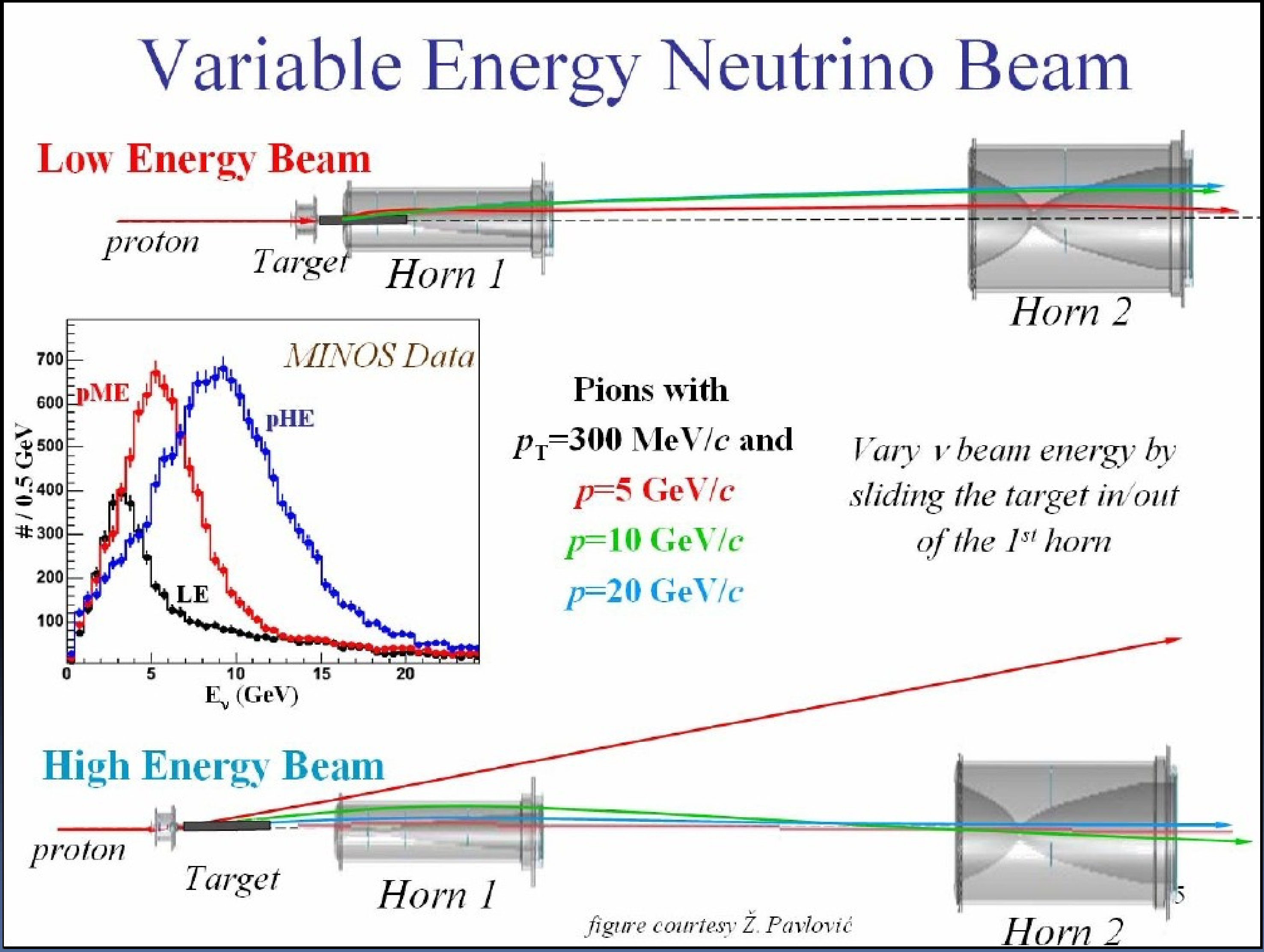
- Is it possible (rates, efficiencies, backgrounds) ? Beam (intensity, spectrum, composition), detailed detector design, analysis techniques..
- Is it affordable ?
- Is it important/interesting enough to bother ?

NuMI Beam and Near Detector Hall





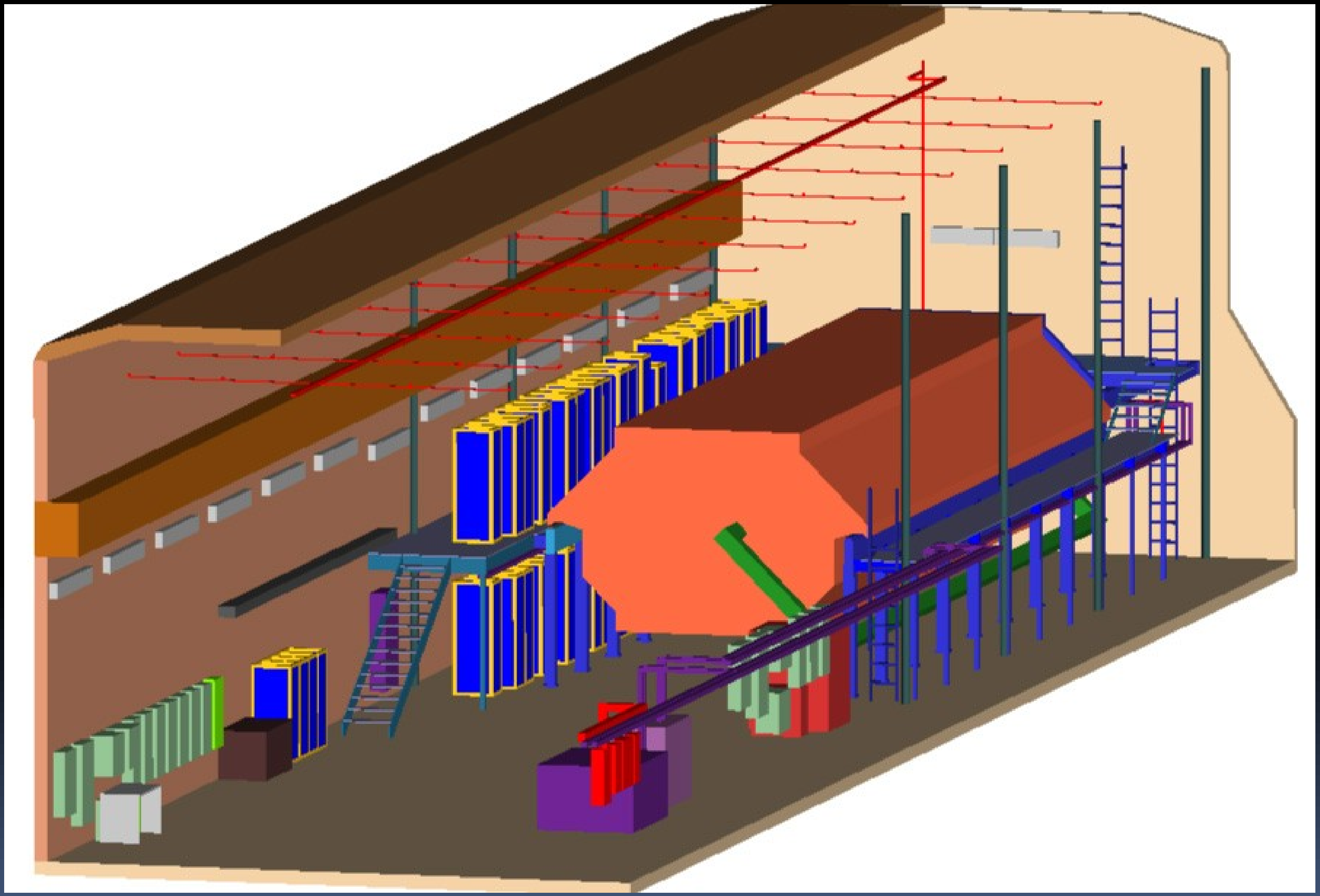
NuMI Neutrino Beam



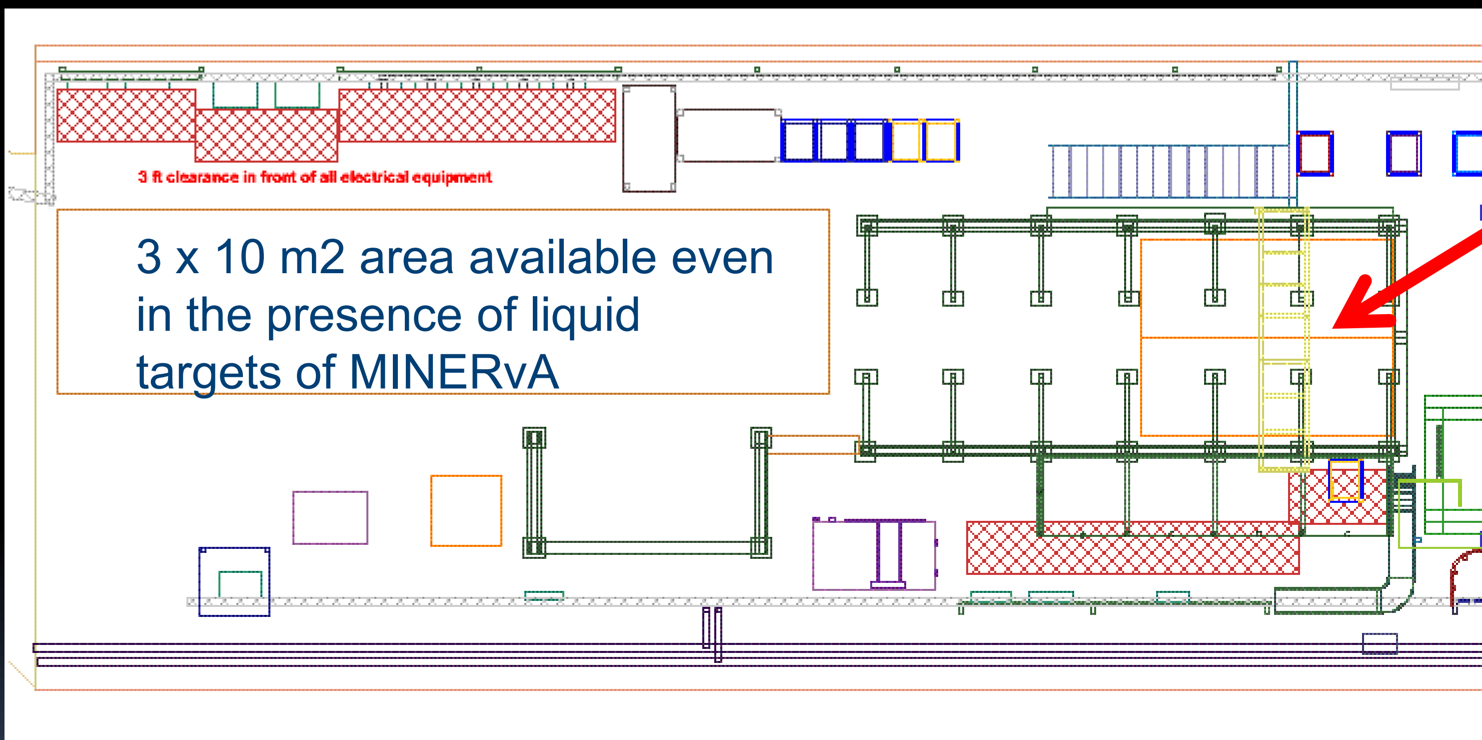
NuMI Neutrino Beam

- Constructed and operating (MINOS, MINERvA)
- Flexible design, adjustable beam energy and spectrum
- 370 kW power
- Major intensity upgrade for NOvA (700 kW)
- Fix the design, limit the flexibility of the future beam, given the well defined physics program (NOvA)
- → If some new experiment is to e contemplated it is important to include the possible requirements into the design process for the upgraded NuMI beam (for example: energy spectrum, antineutrino component)

The MINOS Experimental Hall, as built



MINOS Near Detector Hall, Now



MINERvA

Achieving the Sensitivity: Backrounds

- The dominant beam related backgrounds:
  - Tau neutrinos component of the neutrino beam

  Tau neutrinos are produced from decays of charm particles produced by the primary protons.
  charm ~ 30 at 450 GeV, ~ 5 at 120 GeV;
  10-7
  - Anti-charm produced by antineutrinos in the beam

  May require a reduction of the intrinsic antineutrino component of the beam. Plug?

Achieving the Sensitivity: Detection Efficiency, Detector Backgrounds

- Requires detailed detector optimization, including the beam design
- A lot of practical experience from OPERA design, construction and operation. Need good feedback

	CHORUS	OPERA	MINSIS
Target Mass	800kg	2000ton	10 ton?
Emulsion Mass	800kg	30ton	1~10 ton
Cost		~100 M$	????

Emulsion Scanning Technology

	CHORUS	OPERA	MINSIS
Scan Area	1 m^2/4year	100m^2/year	20m^2???
# of events	500K/4year	4K/year	100M
# of Films	600	9.3M	100K-1M
System	NTS / UTS	SUTS	SUTS
Speed	~1cm2/h	100cm2/h	100cm2/h
LOAD	5 Years	1 Year	30 months

Much faster system ~5000cm2/h (SQTS) for dark matter, double beta experiment and Muon radiography under development in Nagoya. (M. Nakamura)

Analysis – Detector Design Interactions

- Past mindset: Scanning is a bottleneck, need a detector capable of finding the interactions and directing the measurement process
- Future mindset?: self contained emulsion detector, complete scan/analysis of the entire volume? Huge statistics of neutrino events as a by-product with simpler detectors ?

By-products?

- Charm Physics??

  D0-D0bar Oscillation?

  Charmed penta-quark study ?

  Charmed hadron mean free path ?

  Charmed Nucleus study?

Initial thoughts of M. Nakamura. Very important aspect of the experiment.

Thoughts on the Detector Design, Optimzation, Protoyping…

- Start with the OPERA design
- Evaluate the background rejection capability
- Complement with silicon tracker (a la ESTAR)
- If necessary make the lead plates much thinner (50 microns steel?)
- Construct prototypes, use the existing NuMI beam for evaluation
- Holographic method for emulsion scanning (Andrew Sonnenschein) ?
- …

Very Preliminary Impressions

- A new experiment searching for the tau appearance at short baseline using the NuMI neutrino beam with the sensitivity of the order of 10^{-6} is possible and quite realistic.
- Detailed and very careful studies necessary to optimize the ultimate experiment and to determine its physics potential.
- The present OPERA experiment the primary source of inspiration and of the critical evaluation of the detection efficiency and background rejection estimates.
- But.. Construction, operation and analysis of such an experiment does require a significant effort and commitment of a large team of people.

Is It Worth Doing?? Part I

- A positive result would have a huge impact on our understanding of the particle physics. It would be a proof of some physics beyond the current standard model. It would be even better if some specific scenarios could be established? Is it a consequence of some sterile neutrinos? Or leptoquarks? Or SUSY? Or charged higgses? Is this possible to tell?? How doe it complement the possible discoveries at the LHC? Or, perhaps, on the contrary, taking all of the existing limits and some sensible assumptions, the existence of such a process at the level of 10^{-6} or higher can be already excluded?

Is It Worth Doing?? Part II

- Suppose that after a heroic effort the experiment will demonstrate that the tau appearance process is suppressed by more than a factor of 10-6 with respect to standard neutrino interactions. Will anybody care? What sort of models will it exclude? What phase space in the parameters space? How likely is it that such a limit will be interesting at the time it can be established (say 2017?)

Establishing of the physics motivation for such a proposal is the most important step towards such a putative experiment.

Synergies

- ‘OPERA crowd’ – large group, expertise, existing detector, large investment in emulsion snanning and analysis, large amount of emulsion unsused after the end of the experiment.. MINSIS = ActII of OPERA?
- ‘Short baseline oscillation search crowd’ – ESTAR, COSMOS, TOSCA people. Efficiency and background rejection studies of direct applicability to MINSIS, possible enhancement of the OPERA-like detector technology
- ‘LBNE/Neutrino factory near detector crowd’ – MINSIS as an R&D/prototype project for the future experiment at the LBNE/neutrino factory

A High Resolution ν Near-Detector for LBNE: Prompt ν_μ, $\nu_e \rightarrow \nu_\tau$

Sanjib R. Mishra & Roberto Petti, Carolina

✳ Questions regarding the PMNS Matrix Elements

❧ Θ_{13} Sensitivity

❧ Sensitivity

❧ ν-Mass Hierarchy

❧ Resolving degeneracies

⇒ *Need systematic precision & redundancy*

✳ Beyond PMNS

❧ Θ_{23} = 45^0 ?

❧ CPT Violation ?

❧ High Δm**2 Oscillation ?

❧ Phenomenon that defies the Zeitghist

✳ The familiar, beautiful neighborhood

❧ Cross-sections, PDFs, (p)QCD

❧ Sin**2(Θ_W): precision commensurate with Colliders

❧ Sum rules, Isospin Physics

❧ Searches: Prompt ν_μ, $\nu_e \rightarrow \nu_\tau$ // $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

❧ Heavy neutrinos

❧ ....

❧ Rewriting the ν-text-book

THE HiResMν CONCEPT

- *Evolution from the NOMAD experiment;*

- *High resolution spectrometer with a dipole magnetic field:*

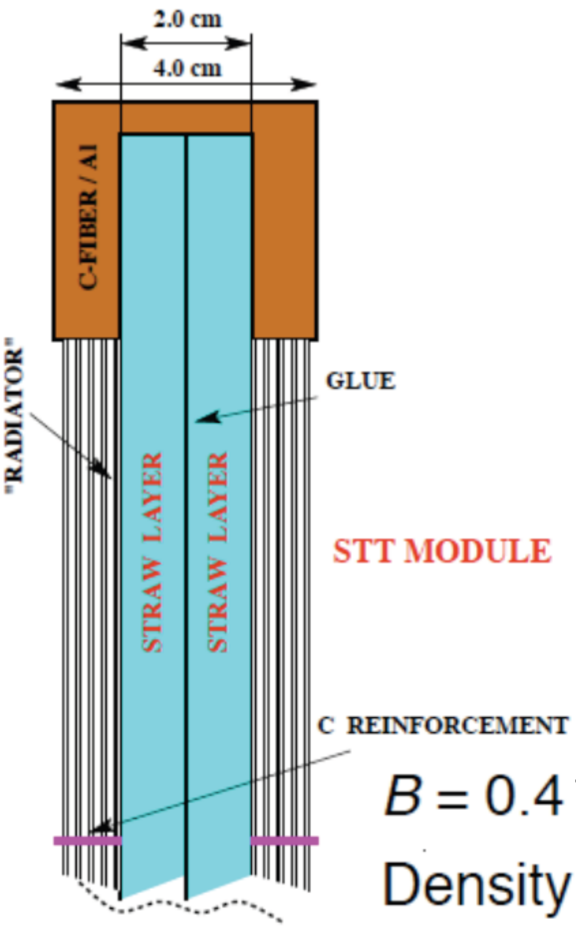
$$B = 0.4T$$

- *Low density "transparent" tracking with target embedded:*

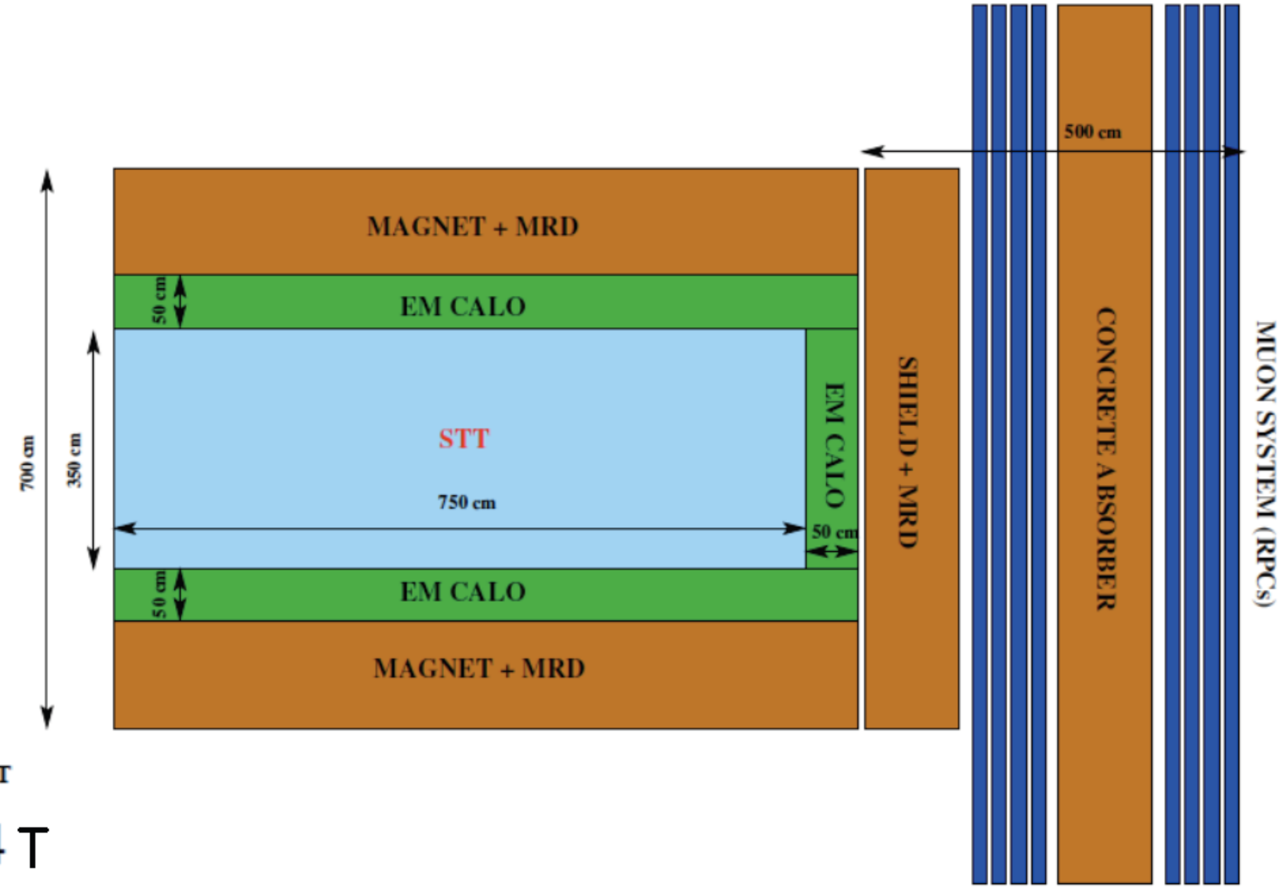
$$1X_0 \sim 5m \quad \rho \sim 0.1g/cm^3$$

- *Combined particle identification & tracking to reconstruct all charged particles and γs produced in neutrino interactions;*

ELECTRONIC BUBBLE CHAMBER WITH *10^8* EVENTS



STT MODULE



$B = 0.4$ T

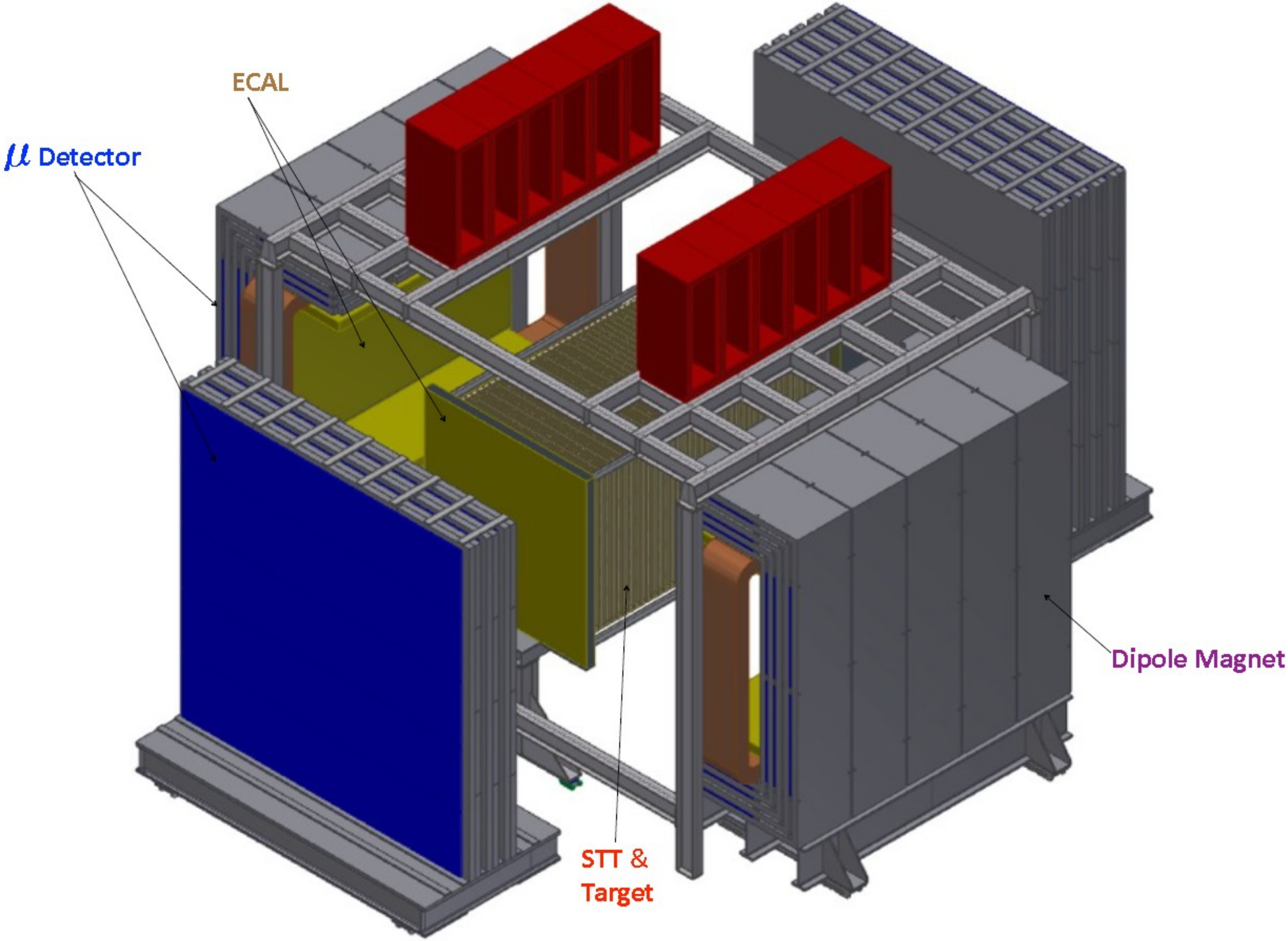
Density = 0.1 g/cm3, 85% in the radiator foils.

Transition Radiation ↠ Electron ID ⇒ γ (w. Kinematics)

dE/dx ↠ Proton, π, K ID

Magnet/Muon Detector ↠ μ

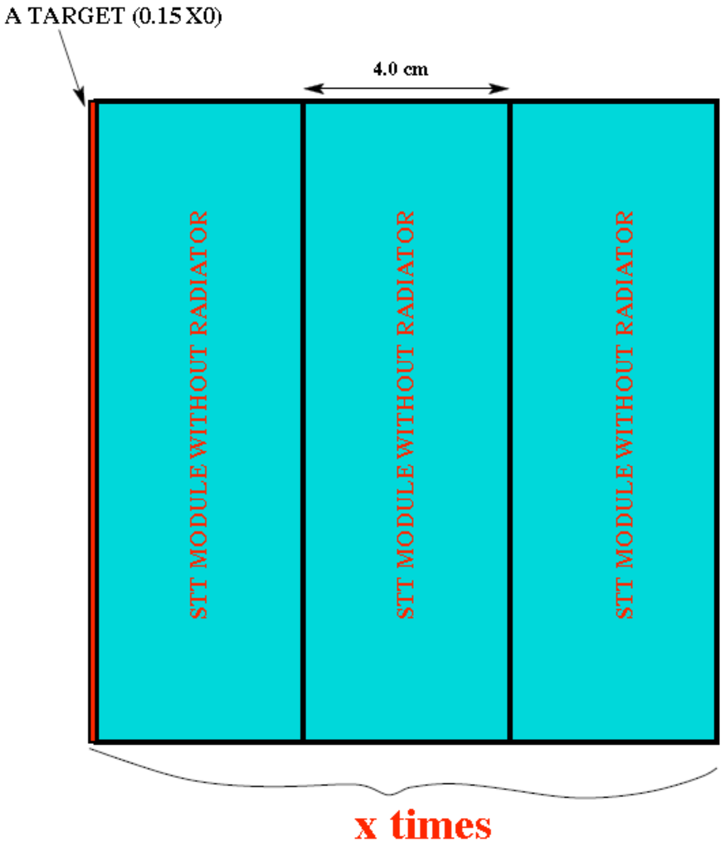
$\mathscr{H}$IRESMNU: Near Detector for LBNE



MEASURING NUCLEAR EFFECTS (Ar, Fe, Ca .. . targets upstream)

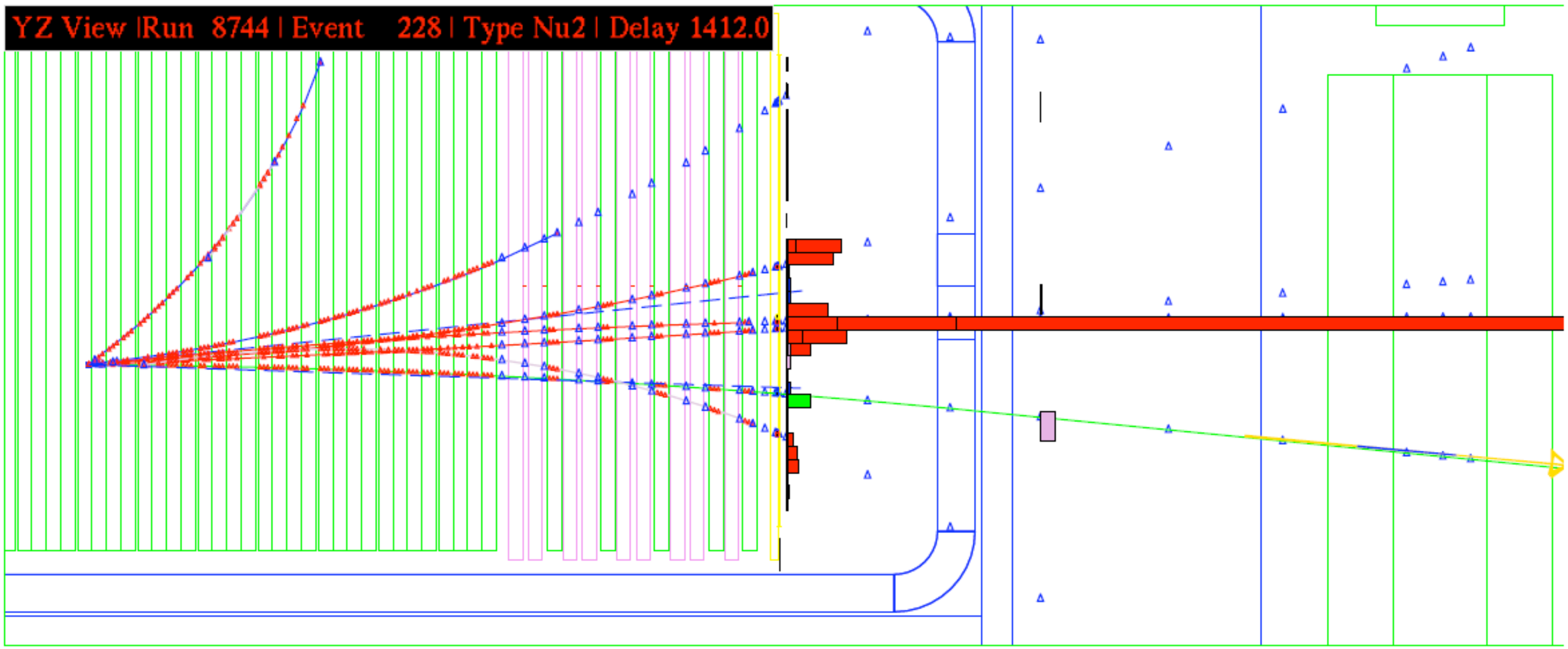
- *Measure the A dependence (Ca, Cu, H_2O, etc.) in addition to the main C target in STT:*
  - *Ratios of F_2 AND xF_3 on different nuclei;*
  - *Comparisons with charged leptons.*

- *Use $0.15X_0$ thick target plates in front of three straw modules (providing 6 space points) without radiators. Nuclear targets upstream.*
  - *For Ca target consider $CaCO_3$ or other compounds;*
  - $\boxed{\text{OPTION}}$: *possible to install other materials (Pb, etc.).*

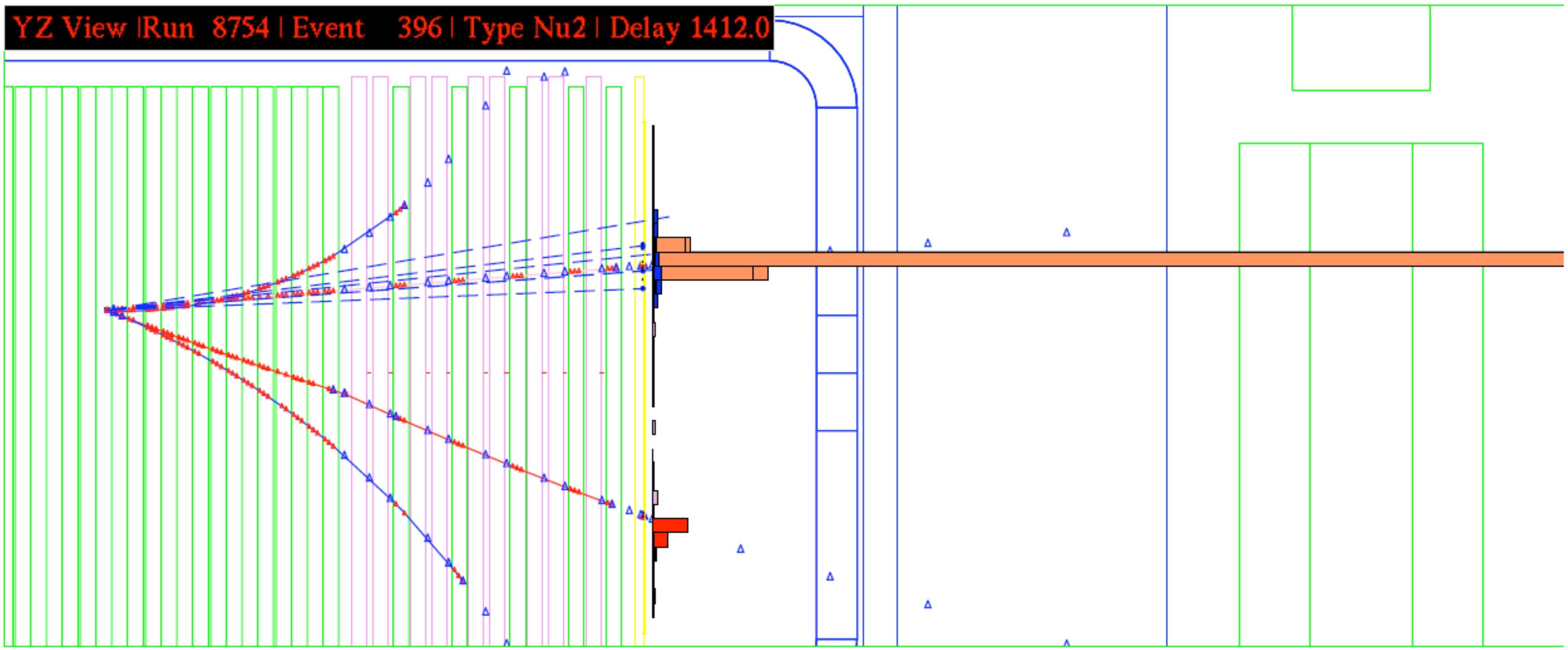


South Carolina Group

A ν_μ CC candidate in NOMAD



A $\bar{\nu}_e$ CC candidate in NOMAD



Improvement over NOMAD: The HIRESMNU Idea

- *Improved Tracking of Charged Particles*
  - x6 more hits in the Transverse-Plane (X-Y)
  - x2 more hits along Z-axis

- *Improved Electron/Positron ID*
  - Continuous TR providing e+/e- ID

- *Improved 4π Calorimetry*
  - Downstream ECAL: fine Longitudinal & Transverse segmentation
  - Barrel & Upstream ECAL

- *Improved 4π μ-ID*
  - 4π-Coverage: min-P_μ ➾ 0.3 GeV

Beam and Statistics: Caveat: Run HE option for 3-years

- *τ Threshold ~0.2 (same as Cosmos) (1/2.5 in threshold suppression)*

- *Factor of x100 higher stat. compared to NOMAD*
  - *4π-ECAL (*Downstream, Barrel, & Upstream*); 4π-μ Coverage*

NOMAD -vs- HIRESMNU

- Tracking Charged Particles ⇒
- Electron/Positron ID ⇒
- Calorimetry ⇒
- μ-ID ⇒
- Trigger ⇒

Sub-Detector	NOMAD	HiResMnu	Improvement
Tracking		$\times$6 more hits in X-Y $\times$2 more hits along Z	$\times$2 higher QE-Proton Eff. $e^{\pm}$ down to 80 MeV γ-Conv. Reconstruction
TR: Electron-ID	Downstream	Continuous	$\simeq \times 3$ $e^{\pm}$-Eff
Calorimetry Segmentation E-shower Resolution	Downstream No Longitudinal Transverse $3\%/\sqrt{E}$	4π Coverage Fine Longitudinal Finer Transverse $6\%/\sqrt{E}$	Much better converage $e^{\pm}/\pi$ Separation Better miss-P_T Powerful 'Dirt'-Veto Poorer resolution
μ-ID	Downstream $P_\mu \geq 2.5$ GeV	4π Coverage	P_μ down to 0.3 GeV
Trigger	Downstream No Cal.Trigger	Continuous in STT Calorimetric Trigger	P down to 0.1 GeV $E \simeq 0.3$ GeV

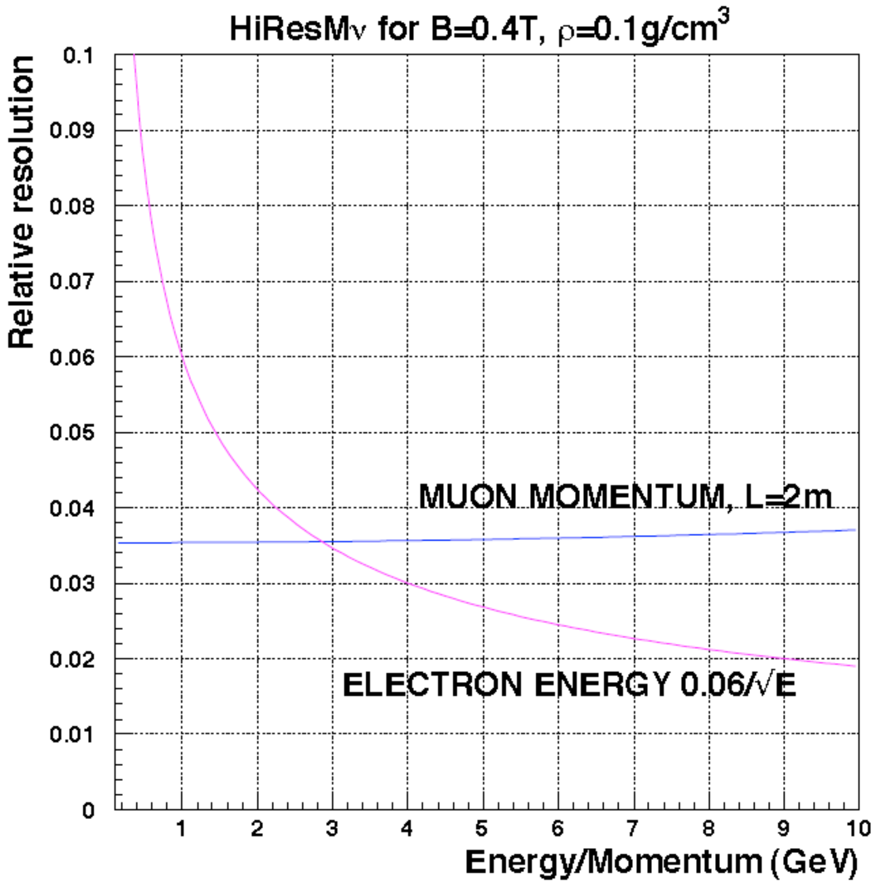
NOMAD versus HiResMnu

Resolutions in HiResMν

- $\rho \simeq$ 0.1gm/cm^3
- Space point position $\simeq$ 200μ
- Time resolution $\simeq$ 1ns

- CC-Events Vertex: Δ(X,Y,Z) $\simeq$ *O*(100μ)
- Energy in Downstream-ECAL $\simeq$ 6%/$\sqrt{E}$
- μ-Angle resolution (~5 GeV) $\simeq$ *O*(1 mrad)

- μ-Energy resolution (~3 GeV) ~ 3.5%
- e-Energy resolution (~3 GeV) ~ 3.5%



NOMAD's Search of $\nu_\mu \rightarrow \nu_\tau$

✳ *Understanding the Control-samples*

- Data-simulator technique: Control-Data/MC provide the calibration
- x2 more hits along Z-axis (No τ +)

✳ *Completely blind analysis*

- Divide search into Low- and High-background regions

✳ *Multivariate analysis: Pt-balance, track-reconstruction, missing-particles*

✳ *Improved 4π μ-ID*

- 4π-Coverage: min-Pμ → 0.3 GeV

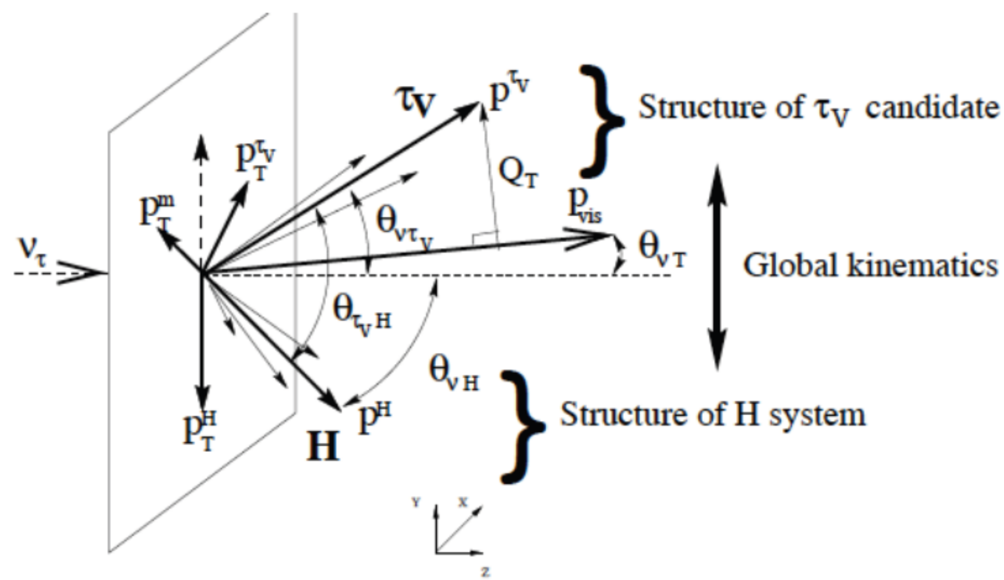


Fig. A.1. Definition of the NOMAD kinematics for a ν_τ CC event.

NOMAD search dominated by '0' background channels:

Nucl.Phys. B611 (2001) 3-39

Analysis			Bin #	Tot bkgnd	Data	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$
$\nu_\tau e \bar{\nu}_e$	DIS		III	$0.18^{+0.18}_{-0.08}$	0	680	15.0
			VI	0.16 ± 0.08	0	1481	32.7
($E_{\text{vis}} < 12$ GeV)			II+III+VI	0.27 ± 0.13	0	665	8.7
$\nu_\tau h(n\pi^0)$	DIS	0γ	III	$0.05^{+0.60}_{-0.03}$	0	288	6.9
		0γ	IV	$0.12^{+0.60}_{-0.05}$	0	1345	31.1
		1γ	III	$0.07^{+0.70}_{-0.04}$	0	223	5.7
		1γ	IV	$0.07^{+0.70}_{-0.04}$	0	1113	26.6
		2γ	IV	$0.11^{+0.60}_{-0.06}$	0	211	4.9
		$1/2\gamma$	III	$0.20^{+0.70}_{-0.06}$	1	707	16.9
		$0/1$-2γ	IV	$0.14^{+0.70}_{-0.06}$	0	1456	34.2
$\nu_\tau 3h(n\pi^0)$	DIS	$3h$	V	$0.32^{+0.57}_{-0.32}$	0	675	16.6
Total				$1.69^{+1.85}_{-0.39}$	1	8844	199.3